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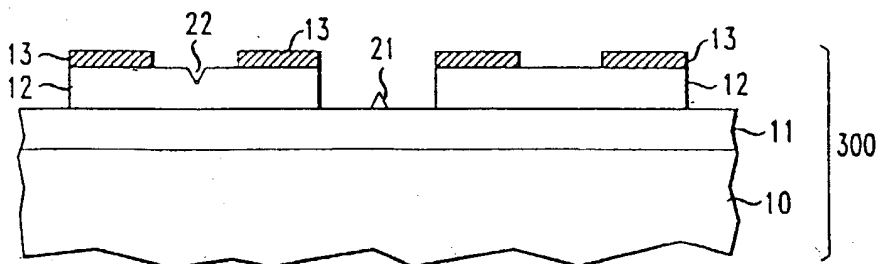
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(54) **Phase-shifting lithographic masks having phase-shifting layers of differing compositions.**

(57) A phase-shifting lithographic mask (500 or 600), for use in conjunction with optical radiation of wavelength  $\lambda$ , has a transparent substrate (10) upon which are successively located a bottom  $(2m+1)\pi$  radian phase-shifting layer (11) and a patterned top  $(2n+1)\pi$  radian phase-shifting layer (12) each having at least approximately the same refractive index at the wavelength  $\lambda$  as that of the substrate. A more finely patterned, opaque chromium layer (13) is located on the patterned top phase-shifting layer. The bottom phase-shifting layer is chemically different from both the substrate and the top layer, in order to provide either etch-stopping or end-point etch detection during subsequent dry ion beam millings—as with gallium ions—of either or both of the layers, for the purpose of mask repair. For example, the substrate is quartz (silicon dioxide), the bottom phase-shifting layer is calcium fluoride, and the top phase-shifting layer is silicon dioxide. Remnants of the gallium then can be removed, if need be, from both the exposed portions of the substrate and of the bottom layer—such as by forming indentation regions (52; 51) by means of successive etchings, for example, with HF and HCl, respectively, for respective prescribed time intervals having a ratio such that the relative phase shifts of the substrate and both phase-shifting layers are not disturbed by the respective etchings.

FIG. 2



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FIG. 4

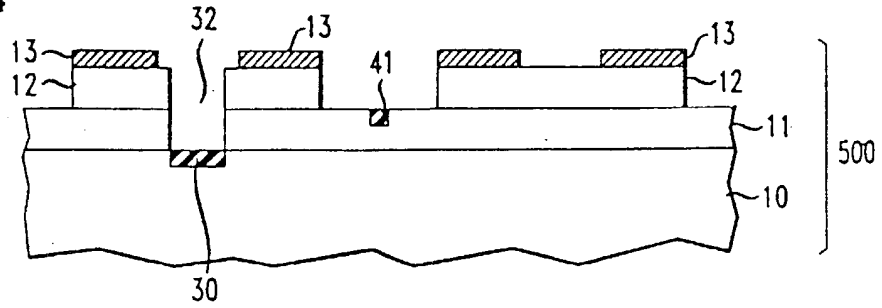
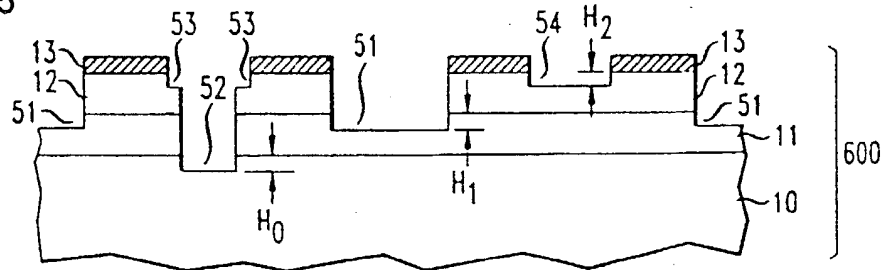


FIG. 5



## Background of the Invention

This invention relates to lithography, especially optical lithography, such as that used for fabricating semiconductor integrated circuit and other devices. More particularly the invention relates to patterned mask structures and to methods of making such structures, typically for use in optical lithography systems for fabricating such devices. These masks are also called "reticles" particularly when used for forming optical images on photoresist layers in such optical lithographic systems having magnifications different from unity.

In order to improve the resolution of such masks when used as the reticles in such systems, in the prior art phase-shifting lithographic masks have been taught. A phase-shifting mask comprises various regions that impart various phase shifts to the optical radiation that originates from an optical source and propagates through the mask in the system. More specifically, these phase-shifting masks have opaque and transparent regions. The transparent regions typically have at least two different thicknesses suitable for imparting at least two different phase shifts (each relative to the ambient atmosphere, typically air), typically equivalent to 0 and  $\pi$  radians, to the optical radiation (of wavelength  $\lambda$ ) propagating through the mask when it is being used as the reticle. The expression for the phase shift of a layer is given by  $(n-l)d$ , where  $n$  denotes the refractive index of the layer,  $d$  denotes the thickness of the layer, and the refractive index of the ambient is assumed to be equal to unity.

In order to facilitate repair of a phase-shifting mask structure, a variety of such mask structures has been proposed in prior art. A typical such phase-shifting mask structure 200 is depicted in FIG. 1. The structure 200 is an extension of the concepts taught in a paper by N. Hasegawa et al., entitled "Submicron Photolithography using Phase-Shifting Mask-Shifter Defect Repair Method," published in Fourth Hoya Photomask Symposium, Japan. This structure 200 includes a transparent quartz substrate 10, a pair of transparent silicon dioxide bottom and top phase-shifter (phase-shifting) layers 7 and 9, respectively, and a patterned opaque chromium layer 13. The patterning of the opaque layer 13 is in accordance with the desired optical image to be formed when the mask is used in the optical lithographic system. A bottom etching end-point detection layer 6 and top etch-stopping layer 8, each typically made of tin oxide, respectively, separate the quartz substrate 10 from the bottom phase-shifter layer 7, and the bottom phase-shifter layer 7 from the top phase-shifter layer 9. The phase-shift introduced by the top phase-shifting layer 9 is equal to  $\pi$  radian; the sum of the phase shifts introduced by the bottom phase-shifting layer 7 and the bottom end-point detection layer 8 is also equal to  $\pi$  radian.

The structure 200 contains protruding and indentation defect regions 21 and 22, respectively. The purpose of the bottom end-point detection layer 6 is to enable repair of the mask structure 200--insofar as the indentation defect region 22 is concerned--by a process of etching (ion milling) the defect region (and perhaps its neighborhood) down to the bottom end-point detection layer 6 without (undesirably) penetrating farther downward, as explained more fully below. The purpose of the top etch-stopping layer 8 is to enable patterning, as by anisotropic dry etching, of the top phase-shifter layer 9 without the etching undesirably penetrating down into the bottom phase-shifting layer 7. In addition, the top etch-stopping layer 8 can serve the function of end-point detection during repair of the mask structure 200--insofar as the protruding defect region 21 is concerned--by a process of etching (ion milling) without penetrating farther downward than the bottom surface of the defect region 21 itself.

In order to repair the mask structure 200--i.e., to remove unwanted phase-shifting effects caused by the defect regions 21 and 22--first the protruding defect region 21 can be removed, as by focused ion beam etching (ion milling) that scans the top surface of the top etch-stopping layer 8. The milling is terminated as soon as secondary ions or secondary electrons being emitted and detected during the ion milling begin to shift from those known to be emitted by the material of the defect region 21 to those known to be emitted by the material of the top etch-stopping layer 8. Then the indentation defect region 22 is removed by anisotropically (vertically) etching it, together with a neighborhood of it, through both the phase-shifting layers 9 and 7 as well as the top etch-stopping layer 8, down to the top surface of the bottom end-point detection layer 6 but not at all penetrating it. In this way, the resulting phase shift associated with the resulting hole penetrating through the bottom and top phase shifter layers 7 and 9 plus the top etch-stopping layer 8 is equal to  $\pi$  radian +  $\pi$  radian =  $2\pi$  radian--i.e., equivalent to a zero phase shift, as is desired.

The foregoing technique suffers from one or more of the following shortcomings. First, the optical absorptions by the top etch-stopping layer 8 and of the bottom end-point detection layer 6 can be undesirably high, especially if the wavelength  $\lambda$  is in the deep ultraviolet (typically the 248 nm optical wavelength emitted by an excimer laser source), and hence the overall optical transmission of the structure 200 can become undesirably low. Second, the refractive index discontinuities at various interfaces between the different materials of the various layers in the structure 200 can give rise to undesirable high-amplitude optical reflections, which again can result in undesirably low overall optical transmission. Third, the complexity of fabrication, owing to the etch-stopping layer 8 and the bottom end-point detection layer 6, can undesirably add to production costs, and also

can lower production yields because of unwanted pinholes that can exist in these layers. Therefore, it would be desirable to have a phase-shifting mask structure for use in the optical lithographic system that mitigates the shortcoming of this prior art.

## Summary of the Invention

This invention is defined in claims 1 and 4. Embodiments of the invention are given in the dependent claims.

## Brief Description of the Drawing(s)

FIG. 1 is a cross-sectional elevational view of a phase-shifting mask structure in accordance with prior art;

FIGS. 2-5 are cross-sectional elevational views of various stages of a phase-shifting mask structure as it is being repaired in accordance with a specific embodiment of the invention.

Only for the sake of clarity, none of the drawings is to scale. Elements that are similar or the same in different Figures are denoted by the same reference numerals.

## Detailed Description

A phase-shifting mask structure 300 (FIG. 2) in accordance with an embodiment of the invention is to be repaired, in order to form a repaired phase-shifting mask structure 600 (FIG. 5) for use as the reticle in an optical lithographic system. This structure 300 differs from the structure 200 in that the etch-stopping layers 6 and 8 are omitted and the (unpatterned) bottom phase-shifting layer 11 is chemically different from both the substrate and the (patterned) top phase-shifter layer 12. Nevertheless, it is important that the refractive indices at the optical wavelength  $\lambda$  of the substrate 10 and of both bottom and the top phase-shifting layers 11 and 12 be mutually at least approximately equal at the wavelength  $\lambda$ , in order to prevent undesirably large amplitude optical reflections either at the interface between the substrate 10 and the bottom phase-shifting layer 11 or at the interface between the bottom and top phase-shifting layers 11 and 12. Also, the (uniform) thicknesses of the bottom and the top phase-shifting layers 11 and 12 respectively, typically are at least approximately equivalent to optical phase shifts of  $\phi_1 = (2m+1)\pi$  and  $\phi_2 = (2n+1)\pi$  at the optical wavelength  $\lambda$ , where  $m$  and  $n$  are integers, preferably both equal to zero. More important, the sum of these phase shifts ( $\phi_1 + \phi_2$ ) should be equal to  $2p\pi$ , where  $p$  is an integer.

For example, the following table indicates sets of choices of materials:

Substrate 10	Bottom Layer 11	Top Layer 12
Quartz	MgF <sub>2</sub>	SiO <sub>2</sub>
Quartz	CaF <sub>2</sub>	SiO <sub>2</sub>
Quartz	$x\text{SiO}_2 + (1-x)\text{Al}_2\text{O}_3$	SiO <sub>2</sub>

Typically,  $x$  is in the approximate range of between 0.3 and 0.95 by molecular number. The top layer 12 of (pure) SiO<sub>2</sub> can be deposited by means of chemical vapor deposition (CVD); whereas the bottom layer of (the mixture)  $x\text{SiO}_2 + (1-x)\text{Al}_2\text{O}_3$ , or of (the pure) MgF<sub>2</sub>, or of (the pure) CaF<sub>2</sub> can be deposited by means sputtering from suitable targets. The top and bottom layers are advantageously, as indicated, different in their respective chemical compositions, in order to enable end-point etching detection, as by detection secondary ions or secondary electrons, or etch-stopping during patterning of the top layer 12.

The bottom phase-shifting layer 11 typically has a defect region 21 (FIG. 2) in the form of excess material of the top phase-shifting layer 12; whereas the top phase-shifting layer 12 has a defect region 22 in the form of an indentation. Although the defect regions 21 and 22 are both depicted in FIG. 2 as having triangular shapes, other shapes are possible independently for each of them. Typically, the location each of the defect regions is detected by means of a two-dimensional scanning optical microscope.

In order to remove the defect region 22, a focused gallium ion beam (not shown) is directed point-by-point at this defect region (as well as perhaps a surrounding neighborhood) but not at the defect region 21 (or at its surrounding neighborhood). This beam thus forms, by the process of ion milling, a recess region 32 penetrating entirely through the top and bottom phase-shifting layers 12 and 11, respectively, down to the top surface of the substrate 10. This ion milling process is immediately terminated as soon as the detected chemical by-prod-

ucts, or secondary ions or electrons, of the process begin to shift from those known to be emitted by the material of the bottom phase-shifting layer 11 to those known to be emitted by the material of the substrate 10, in order to guard against significantly penetrating the top surface of the substrate 10 during the ion milling process. Also, it is advantageous that the ion milling rate through the material of the substrate 10 is significantly lower than the rate through the material of the bottom layer 11, to further guard against the top surface of the substrate 10 being significantly penetrated by the ion milling process. In this way the structure 400 (FIG. 3) is obtained. Because of the gallium ions contained in the ion beam, in this structure 400 a nontransparent stained region 30--located in the region underlying the areas where the ion beam was directed--has been formed. It can be removed later. At any rate, the ion beam has thus produced a recess region 32 cutting through an area portion of the top and bottom phase-shifting layers 12 and 11, respectively.

Next, the focused gallium ion beam is directed at the defect region 21, in order to remove it by ion milling. This ion milling is terminated as soon as the detected by-products, or the secondary ions or electrons, of the milling process begin to shift from those known to be emitted by the material of this defect region 21 to those known to be emitted by the material of the bottom phase-shifting layer 11. Thus, the resulting ion milling removes the defect region 21--again, however, leaving another nontransparent stained region 41 in the resulting structure 500 (FIG. 4).

The structure 500, despite the presence of the stained regions 30 and 41, is thus a repaired version of the original structure 300 and can be used as the reticle in the optical lithographic system, especially if the ion beam is such as not to produce a degree of staining that undesirably degrades optical performance of the structure 500. When used as the reticle in the optical lithographic system, the phase-shifting mask structure 500 is oriented typically with its substrate 10 being located closer to the optical source in the system than its patterned chromium layer 13. On the other hand, if it is desired to remove the stained regions 30 and 41, and thus produce a stain-free phase-shifting mask structure 600 (FIG. 5), a thickness equal to  $H_2$  is to be removed both from the top phase-shifting layer 12, a thickness equal to  $H_0$  from the substrate 10, and a thickness equal to  $H_1$  is to be removed from the bottom phase-shifting layer 11. Typically  $H_0$  and  $H_1$  (as well as  $H_2$ ) are of the order to 20 nm. Advantageously, both  $H_0$  and  $H_1$  are greater than the depths of the respective stained regions 30 and 41. Advantageously also,  $H_0$ ,  $H_1$ , and  $H_2$  at least approximately satisfy the mutual relationships:

$$H_0(n_0 - 1) = H_1(n_1 - 1) = H_2(n_2 - 1) \quad \text{eq.(1),}$$

where  $n_0$  is refractive index of the substrate 10, and  $n_1$  and  $n_2$  are the refractive indices of the bottom or top phase-shifting layers 11 and 12, respectively--the refractive indices  $n_0$ ,  $n_1$ , and  $n_2$  all being measured at the wavelength  $\lambda$  to be used in the optical lithographic system. In this way, not only are the stained regions 30 and 41 removed, but the added phase-shifts produced by the resulting added indentation regions 51, 52, 53 and 54 formed, respectively, in the bottom phase-shifting layer 11, the substrate 10, and the top phase-shifting layer 12 also are mutually compensated. The indentation region 52 together with the original recess region 32 (FIG. 4) form a recess-indentation region.

In order to remove the stained regions 30 and 41 and thus produce the stain-free structure 600, by way of example, the thickness  $H_0$  is removed from respective exposed areas of the substrate 10 and of the top phase-shifting layer 12--such as by means of a wet or dry etching process that does not significantly etch the bottom phase-shifting layer 11. (Here the term "not significantly" means that any departure from not etching any of the bottom phase-shifting layer 11 does not introduce any intolerable defects in the optical image formed in the photoresist layer 10, in the optical lithographic system.) For example, if the materials of the substrate 10 and of the top phase-shifting layer are both oxides that etch at the same rate, say silicon dioxide (quartz, or CVD silicon dioxide), and the material of the bottom phase-shifting layer 11 is a fluoride, say calcium or magnesium fluoride, then the etchant can comprise (wet) hydrofluoric acid or a (dry) fluorinated gas mixture of  $\text{CHF}_3$ ,  $\text{CF}_4$ , and  $\text{O}_2$ . Thereby the indentations 52, 53 and 54 are formed--all having the depth  $H_0$ . The actual value of the depth  $H_0$  is then measured, or is known (by experience) from the etching time duration and the etching conditions. In this way, the stained region 30 is removed.

Next, the depth (thickness)  $H_1$ , is calculated from the above equation (1). Then this known (desired) thickness  $H_1$  is anisotropically removed from exposed areas of the bottom phase-shifting layer 11--such as by means of an etching process that does not significantly etch the substrate 10 or the top phase-shifting layer 12. For example, in cases of the above-mentioned materials, the etchant can comprise hydrochloric acid. This etching of the bottom phase-shifting layer 11 is terminated when the (desired) depth  $H_1$  of the resulting indentation 51 is attained--as actually measured or as known (by experience) from the etching time duration and the etching conditions. In this way the stained region 41 is removed, and at the same time the added phase shifts produced by removal of the stained regions 30 and 41 all compensate one another. The structure 600 can then advantageously be used as the reticle in the optical lithographic system, again typically with the substrate 10 being located closer to the optical source than the patterned chromium layer.

Although the invention has been described in detail with respect to a specific embodiment, various mod-

ifications can be made without departing from the scope of the invention. For example, the order of sequence of removal of the stained regions 30 and 41 can be reversed. Also, it is not necessary that the etching process that is used to remove the stained region 30 does not significantly remove any of the material of the bottom phase-shifting layer 11, so long as the ratios of  $H_2$  to  $H_1$  to  $H_0$  in the final structure 600 satisfy equation 1. Similarly, it is not necessary that the etching process that is used to remove the stained region 41 does not significantly remove any of the material of the substrate 10 or of the top phase-shifting layer 12, again so long as the ratios of  $H_2$  to  $H_1$  to  $H_0$  in the final structure 600 satisfy equation 1. Finally, instead of the optical source in the lithographic system, an X-ray source can be used in conjunction with suitable modifications of the other elements located between the source and the (X-ray sensitive) photoresist layer, as known in the art.

## Claims

1. A phase-shifting lithographic mask structure (300; 500; 600), for use in an optical lithographical system utilizing optical radiation of wavelength  $\lambda$ , comprising a transparent substrate (10) having a major surface, CHARACTERIZED BY

a first transparent layer (11) of first material that is chemically different from that of the substrate, located on and contiguous with the major surface;

a second transparent layer (12) of second material that is chemically different from that of the first material, located on and contiguous with the first transparent layer, the second transparent layer being patterned with apertures that penetrate completely through it;

the refractive index at the wavelength  $\lambda$  of the substrate being substantially equal to those of the first and second transparent layers at the wavelength  $\lambda$ , such that optical reflections of the optical radiation at the interface of the substrate and the first transparent layer and at the interface of the first and second transparent layers are insubstantial.

2. A structure in accordance with claim 1 further CHARACTERIZED BY

a recess region (32) penetrating entirely through the second and the first layers, or

a first indentation region (51) penetrating through a first thickness of the first layer and a second indentation region (54) penetrating through a second thickness of the second layer, or

a first indentation region (51) penetrating through a first thickness of the first layer, a second indentation region (54) penetrating through a second thickness of the second layer, and a recess-indentation region (52) penetrating entirely through the second and first layers and through a thickness of the substrate equal to the first thickness, the substrate and the second layer having essentially the same chemical composition.

3. The structure of claim 1 or 2 further CHARACTERIZED IN THAT at least a superposed portion of each of the first and second layers has a uniform thickness and imparting to the optical radiation a total phase shift equal to  $2p\pi$  radian when the radiation is propagating through the structure, where  $p$  is a positive integer.

4. A method of making a phase-shifting lithographic mask structure (300; 500; 600), for use in an optical lithographic system utilizing optical radiation of wavelength  $\lambda$ , having a transparent substrate (10) having a major surface, CHARACTERIZED BY

forming a first transparent layer (11) of first material that is chemically different from that of the substrate, located on and contiguous with the major surface;

forming a second transparent layer (12) of second material that is chemically different from that of the first material, located on and contiguous with the first transparent layer, the second transparent layer having apertures that penetrate completely through it.

5. The method of claim 4 further comprising the step of forming:

a recess region (32) penetrating entirely through the second and the first layers, or

a first indentation region (51) penetrating through a first thickness of the first layer and a second indentation region (54) penetrating through a second thickness of the second layer, or

a first indentation region (51) penetrating through a first thickness of the first layer, a second indentation region (54) penetrating through a second thickness of the second layer, and a recess-indentation region (52) penetrating entirely through the second and first layers and through a thickness of the substrate equal to the first thickness, the substrate and the second layer having essentially the same chemical composition.

FIG. 1

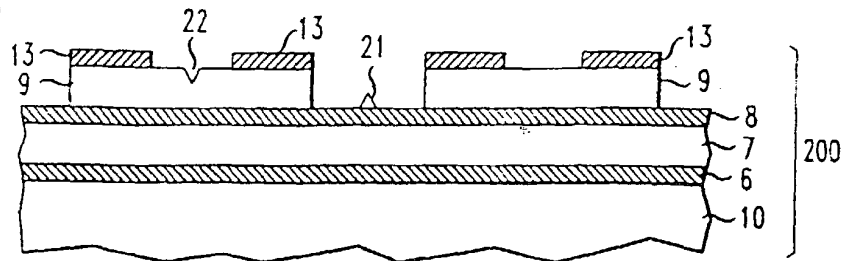


FIG. 2

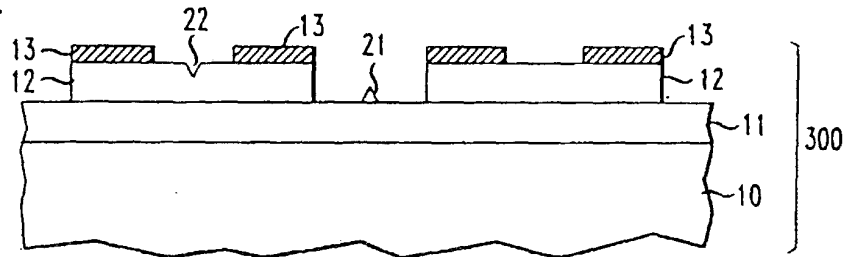


FIG. 3

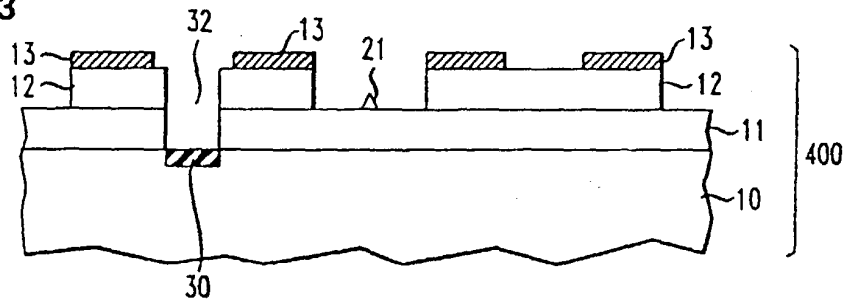


FIG. 4

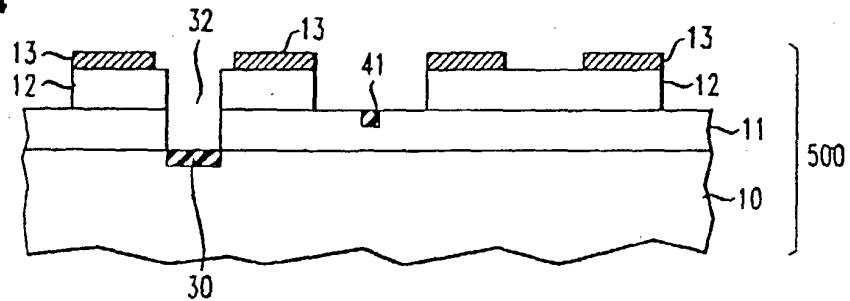
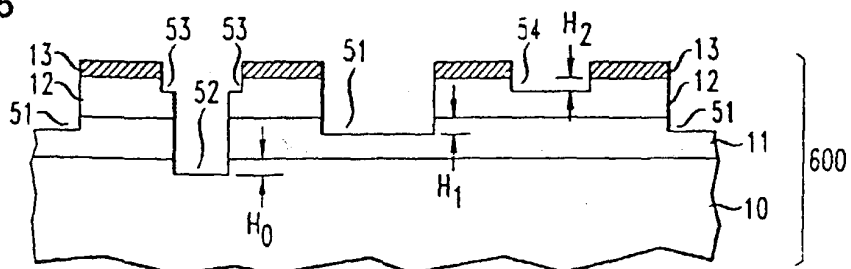


FIG. 5



(19)



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millings--as with gallium ions--of either or both of the layers, for the purpose of mask repair. For example, the substrate is quartz (silicon dioxide), the bottom phase-shifting layer is calcium fluoride, and the top phase-shifting layer is silicon dioxide. Remnants of the gallium then can be removed, if need be, from both the exposed portions of the substrate and of the bottom layer--such as by forming indentation regions (52; 51) by means of successive etchings, for example, with HF and HCl, respectively, for respective prescribed time intervals having a ratio such that the relative phase shifts of the substrate and both phase-shifting layers are not disturbed by the respective etchings.

FIG. 2

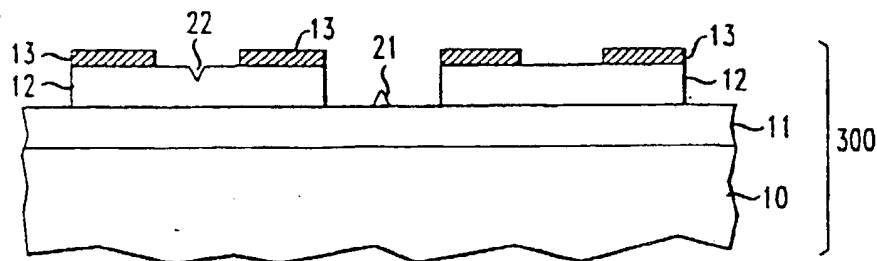


FIG. 4

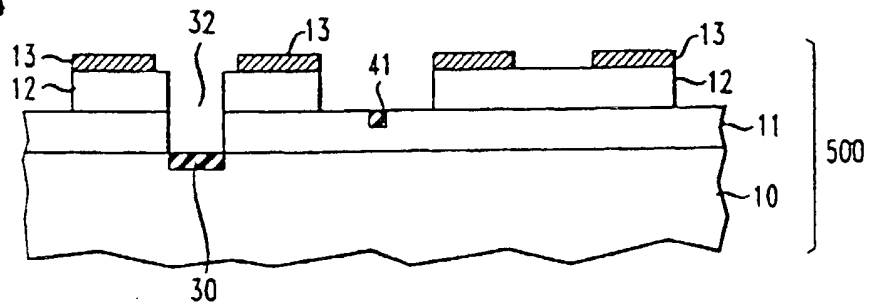
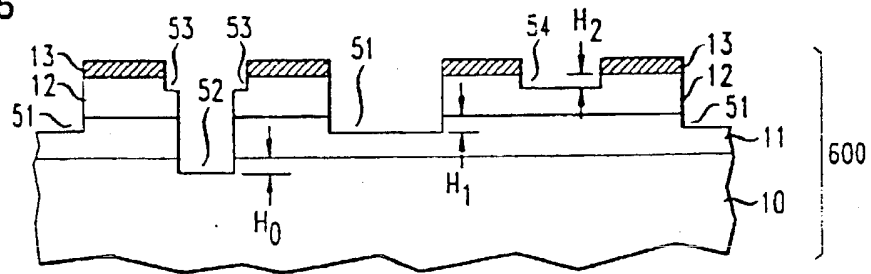


FIG. 5





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# EUROPEAN SEARCH REPORT

Application Number  
EP 93 30 6358

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.5)
A	"Extended Abstracts of 51st Autumn Meeting of the Japanese Society of Applied Physics", JAPANESE SOCIETY OF APPLIED PHYSICS XP002000896 Abstract 27p-ZG-10 by N. Hasegawa, T. Tanaka, Akira Imai and H. Fukuda * page 493 * "& US-A-5362591, Col.12-14, Fig.18-19" ---		G03F1/14 G03F1/00
T	US-A-5 362 591 (A. IMAI ET AL) 8 November 1994 * column 12 - column 14; figures 18,19 * ---		
A	US-A-5 085 957 (MITSUBISHI DENKI KK) ---		
T	DATABASE WPI Derwent Publications Ltd., London, GB; AN 95-221307 XP002000897 & JP-A-07 134 397 (FUJITSU) , 23 May 1995 * abstract *		TECHNICAL FIELDS SEARCHED (Int.Cl.5)
X	PATENT ABSTRACTS OF JAPAN vol. 016, no. 268 (P-1372), 17 June 1992 & JP-A-04 068352 (DAINIPPON PRINTING CO LTD), 4 March 1992, * abstract *	1,2,4,5	G03F
X	PROCEEDINGS OF THE SPIE, OPTICAL/LASER MICROLITHOGRAPHY, SAN JOSE, CA, 11-13 MARCH 1992, vol. 1674, no. 1, pages 216-229, XP000568640 Y. TAKAHASHI ET AL.: "Primary Processes in E-beam and Laser Lithographies for Phase Shifting Mask Manufacturing" * figure 1 * -----	1,2,4,5	
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 23 April 1996	Examiner Haenisch, U
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